The role of conscious control in maintaining stable posture

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Abstract

This study aimed to examine the relationship between conscious control of movements, as defined by the Theory of Reinvestment (Masters & Maxwell, 2008; Masters, Polman, & Hammond, 1993), and both traditional and complexity-based COP measures. Fifty-three young adults (mean age = 20.93 ± 2.53 years), 39 older adults with a history of falling (mean age = 69.23 ± 3.84 years) and 39 older adults without a history of falling (mean age = 69.00 ± 3.72 years) were asked to perform quiet standing balance in single- and dual-task conditions. The results showed that higher scores on the Movement Specific Reinvestment Scale (MSRS; Masters, Eves, & Maxwell, 2005; Masters & Maxwell, 2008), a psychometric measure of the propensity for conscious involvement in movement, were associated with larger sway amplitude and a more constrained (less complex) mode of balancing in the medial-lateral direction for young adults only. Scores on MSRS explained approximately 10% of total variation in the medial-lateral sway measures. This association was not apparent under dual-task conditions, during which a secondary task was used to limit the amount of cognitive resources available for conscious processing. No relationship between postural control and score on the MSRS was found for either older adult fallers or non-fallers. Possible explanations for these results are discussed.

Keywords: Postural control; Movement specific reinvestment; Older adults

1. Introduction

Postural control is enabled by the sensory system, the central nervous system and the musculo-skeletal system (Winter, Patla, & Frank, 1990). The complex interaction between these systems supports upright stance and adaptation to the ever-changing environment (Manor et al., 2010). Postural control has long been considered to be automatic, requiring minimal conscious information processing; however, research during the past two decades, using dual-task methodology (Dault, Frank, & Allard, 2001; Melzer, Benjuya, & Kaplanski, 2004; Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997; Swanenburg, de Bruin, Favero, Uebelhart, & Mulder, 2008), manipulations of attentional focus (e.g., Rotem-Lehrer & Laufer, 2007; Wulf, Landers, Lewthwaite, & Töllner, 2009; Wulf, Töllner, & Shea, 2007) and examination of personality characteristics (e.g., Huffman, Horslen, Carpenter, & Adkin, 2009; Zaback, Cleworth, Carpenter, & Adkin, 2015), has challenged that idea.

Traditionally, postural control has been described by center-of-pressure (COP) displacements during an attempt to stand as still as possible. Greater amplitude and variability of COP is generally thought to reflect higher instability of the body. For example, research has shown that in comparison to young adults, older adults (especially those who have fallen previously) show increased area of sway, higher sway velocity, and more sway variability in medial-lateral and anterior-posterior directions (Bergamin et al., 2014; Hageman, Leibowitz, & Blanke, 1995; Qiu & Xiong, 2015). Reductions in postural stability have been reported in older adults when an additional secondary task that consumes available attention resources has been added (e.g., Marsh & Geel, 2000; Shumway-Cook & Woollacott, 2000). In some cases (e.g., Andersson, Hagman, Talianzadeh, Svedberg, & Larsen, 2002; Riley, Baker, Schmit, & Weaver, 2005), but not in others (e.g., Andersson et al., 2002; Riley et al., 2005), the same effect has been detected in young adults. Differences in balance performance under dual-task conditions suggest that postural control relies on cognitive processing and is therefore not fully automated.

Further evidence of cognitive involvement in balance comes from studies that have manipulated conscious processing of movement during maintenance of stable posture. Wulf and colleagues (Wulf et al., 2009; Wulf, McNevin, & Shea, 2001; Wulf, Mercer, McNevin, & Guadagnoli, 2004), for example, showed that adopting an internal rather than an external focus of attention caused increased postural sway. They argued that adopting an internal focus of attention encourages conscious control of movements, which is likely to interfere with automatic motor control processes. Similarly, people with a higher predisposition to consciously control their movements, as defined by the Theory of Reinvestment (Masters, 1992; Masters & Maxwell, 2008), have been shown to lean further away from a platform edge and sway at larger amplitudes when attempting to maintain stable posture during postural threat conditions (i.e., on an elevated surface; Huffman et al., 2009; Zaback et al., 2015). Huffman et al. (2009) were the first to use a balancing task to show what Masters et al. (1993) have argued earlier '…the automatic processing system in some individuals can be more easily disrupted than in the others…' (p. 656). These findings suggest that in some conditions, or in certain people, maintaining a stable posture utilizes cognitive resources.

Over the past two decades, however, it has become apparent that '…changes in postural sway may reflect things other than changes in stability…' (Fraizer & Mitra, 2008, p. 276), as variability of COP displacement is not always a consequence of uncorrelated random errors (Cavanaugh, Guskiewicz, & Stergiou, 2005; Costa et al., 2007). Consequently, traditional COP-based measures, which disregard the complex dynamics of COP movement, may be inadequate. For example, rather than reflecting instability, higher average sway velocity may be a function of searching for a stable solution (Palmieri, Ingersoll, Stone, & Krause, 2002). Consequently, researchers have employed methods of nonlinear dynamics and fractal analysis from complexity theory to explain and quantify the characteristics of postural sway dynamics. Entropy-based measures (e.g., sample entropy, SampEn) and detrended fluctuation analysis (DFA) are examples of such methods.

SampEn is the negative natural logarithm of the conditional probability that two sequences that are similar for a certain number of data points remain similar at the next data point if self-matches are not included in computing the probability (Richman & Moorman, 2000). SampEn indicates how much each data point depends on the value of previous data points. Lower values of SampEn, therefore, reflect higher self-similarity, or higher regularity, in the time series. DFA quantifies the fractal-like long-range correlation properties in the COP time series (Duarte & Zatsiorsky, 2001; Peng et al., 1994). DFA values close to 1.0 are considered to indicate high complexity, whereas values close to 0.5 or 1.5 indicate low complexity (Duarte & Sternad, 2008; Lipsitz, 2002). In simple terms, both of the measures describe the complex dynamics of COP.

Researchers have argued that complexity is associated with a system's health and reflects the ability to adapt to changes in the environment; higher complexity has been linked to better performance and superior ability to adapt, whereas, lower complexity has been linked to reduced ability to do so (Goldberger, Peng, & Lipsitz, 2002; Lipsitz & Goldberger, 1992; Manor & Lipsitz, 2013). For example, a growing body of evidence shows that loss of complexity is associated with biological aging and/or disease (e.g., Costa et al., 2007; Kang et al., 2009; Manor et al., 2010). It has, therefore, been argued that older adults, especially those who have fallen, display a more constrained mode of postural control compared to young healthy adults. Indeed, some authors have suggested that higher levels of complexity in the COP time series reflect greater 'automaticity' of postural control, but lower levels of complexity reflect greater cognitive involvement (Donker, Roerdink, Greven, & Beek, 2007; Roerdink, Hlavackova, & Vuillerme, 2011; Stins, Michielsen, Roerdink, & Beek, 2009). To date, there is only limited evidence to support this proposition (e.g., Cavanaugh, Mercer, & Stergiou, 2007; Donker et al., 2007), and not all investigators agree with such an interpretation (e.g., Borg & Laxåback, 2010; Duarte & Sternad, 2008).

The present study was conducted in order to examine the relationship between conscious control of movement and traditional and complexity-based COP measures, with an intention to better understand the role of conscious control in maintaining stable posture. We first examined static balance performance of young adults, older adult non-fallers and older adult fallers under single- and dual-task conditions. We then examined the relationship between individual predisposition for conscious control of movement, as defined by the Theory of Reinvestment (Masters, 1992; Masters & Maxwell, 2008), and COP-based traditional and complexity-based measures. We aimed to investigate whether traditional and complexity-based COP measures were associated with conscious movement processing when maintaining stable posture. We anticipated that higher propensity for conscious control of movement would be associated with increased sway velocity, amplitude and area, and with lower complexity (i.e., greater regularity) in the COP time series. We expected to observe such associations during single-task balance but not during dual-task balance, when cognitive resources normally available for conscious control of movement were occupied by a secondary task.

2. Methods

2.1 Participants

Participants consisted of 78 community dwelling older adults and 53 young adults. Young adults (YA; age range 18-35 years, mean = 20.93 ± 2.53 years) were undergraduate students who participated for course credits. Older adults were recruited via local elderly community centers in Hong Kong and by word-of-mouth. Thirty-nine of the older adults had a history of one or more falls over the previous two years and were classified as older adult fallers (OA-F;

age range 65-81 years, mean = 69.23 ± 3.84 years). History of falls was defined as any fall for which a participant was clearly able to identify a timeframe, venue and mechanism. The other 39 older adults did not have a history of falls and were classified as older adult non-fallers (OA-NF; age range 65-77 years, mean = 69.00 ± 3.72 years). Exclusion criteria for older adults included: (1) reported any physical or neurological impairment, (2) static visual acuity worse than 20/40, (3) used walking aids, and (4) scored less than 24/30 on the Cantonese version of the Mini Mental State Examination (Chiu, Lee, Chung, & Kwong, 1994; Folstein, Folstein, & McHugh, 1975). A score greater than or equal to 24 is generally considered to reflect normal cognition (Tombaugh & McIntyre, 1992). Ethical approval was obtained from the local ethics committee and written informed consent was collected from each participant.

2.2 Apparatus

Postural stability was measured using a force-measuring plate (Zebris FDM 1.5, Germany; 55cm x 40cm x 2.1 cm; 50 Hz sampling rate). LabVIEW Application Builder 2010 (National Instruments Inc., Austin, TX) was used to create a tone-counting secondary task that presented high-pitched (1000 Hz) and low-pitched (500 Hz) tones in a randomized order at intervals of 1000ms.

2.3 Procedure

All participants performed dual-task balancing and single-task balancing. In the single-task balancing condition, participants were required to attempt to stand as still as possible for 1 minute on the force-measuring plate by adopting their most comfortable stance, keeping their hands by their sides and looking straight ahead at a blank wall[1]. In the dual-task balancing condition, participants completed the identical task for 1 minute while monitoring and

[1] We decided not to control for stance position and visual fixation point in order to avoid excessive conscious attention to balancing due to possibly unnatural behaviour.

subsequently reporting the number of high-pitched tones presented via computer speakers. Participants were instructed to prioritize the balancing task. Prior to the dual-task condition, participants became familiar with the tone-counting task by completing 1 minute seated practice trials until the discrepancy between number of high-pitched tones presented and recalled/counted was less than 5 tones[2]. None of the participants reported having any difficulties hearing the tones.

2.4 Dependent measures and data analysis

The Movement Specific Reinvestment Scale (MSRS-English/MSRS-Chinese) (Masters et al., 2005; Masters & Maxwell, 2008; Wong, Masters, Maxwell, & Abernethy, 2008; Wong, Masters, Maxwell, & Abernethy, 2009) was used to measure each individual's predisposition for conscious control of movement. The Scale consists of 10 statements designed to evaluate an individual's concerns about their style of moving (e.g., "I am concerned about my style of moving") and process of moving (e.g., "I try to think about my movements when I carry them out"). The items are rated on a 6-point Likert scale ranging from "strongly disagree" to "strongly agree". The cumulative scores range from 10 to 60 points with lower scores indicative of low propensity for reinvestment and higher scores indicative of greater propensity for reinvestment. The MSRS has been shown to have high internal consistency and test-retest reliability (Masters & Maxwell, 2008).

Eight center-of-pressure (COP) measures of postural stability were recorded. Four traditional COP measures included: (1) ellipsoidal area (85.35%) (Area), (2) average velocity, (3) standard deviation of medial-lateral axis (SD-ML), and (4) standard deviation of anterior-posterior axis (SD-AP). A further four sample entropy (SampEn) and detrended fluctuation

[2] The aim of the secondary task was to limit the amount of cognitive resources available for conscious processing of the balancing task. We therefore aimed to ensure that participants were comfortable to perform the secondary task in order to avoid excessive negative effects on balancing. However, performance of the secondary task did not have to be within the 5-tone error rate during the dual-task condition.

analysis (DFA) measures of COP dynamics for medial-lateral and anterior-posterior axes included: (5) SampEn-ML, (6) SampEn-AP, (7) DFA-ML, and (8) DFA-AP.

Sample entropy was calculated as follows (see Ko & Newell, 2016):

$$SampEn(m,r,N) = -ln\frac{C^{m+1}(r)}{C^{m}(r)}$$

where *m* represents the length of the repetition vector that was compared, *r* the similarity criterion, *N* the number of COP data points, and $C^{m}(r)$ the correlation sum. For this study we used the "default" parameter values m = 2 and r = 0.2. Higher values of entropy represent greater complexity (i.e., less regularity).

To assess the DFA exponent (α) that gauges the complexity of COP, first the COP time series was centered to a zero mean and integrated, and then detrended (Ko & Newell, 2016). The data were then chopped into time-scales with an equal number of data points to compute the root mean square (RMS), which was calculated by the difference between the integrated COP and detrended COP as follows:

$$F(ts) = \sqrt{\frac{1}{N}\sum_{t=1}^{N}[COP_{ln}(t) - COP_{De}(t)]^2}$$

where *F(ts)* is RMS at a given time-scale, and COP_{In} and COP_{De} are the integrated and detrended COP, respectively. The DFA exponent α was estimated as the slope obtained by a linear regression of *F(ts)* over time-scale based on log10 transformation.

Univariate statistics for each traditional COP measure (Area, Average velocity, SD-ML, SD-AP) and for each complexity-based COP measure (SampEn-ML, SampEn-AP, DFA-ML, DFA-AP) were computed for young adults (YA), older adult non-fallers (OA-NF) and older adult fallers (OA-F) for single-task (ST) and dual-task (DT) conditions. A 2 (Task condition: ST and DT) X 3 (Group: YA, OA-NF, and OA-F) multivariate repeated measures ANOVA was conducted separately for traditional COP variables and for complexity based COP variables to first examine the differences in balance performance between groups. Significant effects were followed up with Bonferroni corrected pairwise comparisons.

Univariate Analyses of Variance were conducted to examine differences in tone-counting accuracy and MSRS scores between YA, OA-NF and OA-F. Finally, Pearson's product-moment correlation coefficients were computed to examine the associations between MSRS and both traditional and complexity-based COP variables. Significant correlations were followed up with simple linear regression analyses to explore the capacity of MSRS score to predict postural stability. Regression assumptions were checked and satisfied. Statistical significance for all tests was set at $p = .05$.

3. Results

Data were first visually screened using box plots to check for skewness and 'extreme values' (i.e., values more than 3 times the interquartile range). In total, 12 participants (YA = 4, OA-NF = 3, OA-F = 5) were excluded from the subsequent analysis as they displayed 'extreme values' for several postural stability measures. The descriptive characteristics of participants included in further analyses are presented in Table 1.

Table 1 Descriptive statistics of study participants

	Young adults	**Older adult non-fallers**	**Older adults fallers**
Age (yrs)	20.90 (2.62)	68.89 (3.70)	69.00 (3.52)
Gender			
Female	25	28	29
Male	24	8	5
MMSE	-	29.23 (1.11)	29.03 (0.98)
MSRS	40.76 (7.84)	30.53 (15.35)	28.68 (12.43)

Note: All characteristics are reported as mean (SD), except for gender.
Abbreviations: MMSE, Mini Mental State Examination; MSRS, Movement Specific Reinvestment Scale

3.1 ST and DT comparison for traditional COP sway variables

Descriptive statistics for all COP measures for ST and DT performance are presented in Table 2.

Multivariate repeated measures ANOVA revealed no significant interaction between Task condition and Group, $F(8, 228) = 0.54$, $p = .824$, $\eta p^2 = .02$. However, a significant effect of Task condition on balance performance was found, $F(4, 114) = 4.06$, $p = .004$, $\eta p^2 = .13$. Bonferroni corrected follow-up tests revealed less Average sway velocity ($p < .001$) and less SD-AP ($p = .043$) under dual-task conditions compared to single-task conditions. No significant differences were found for Area of sway ($p = .132$) and SD-ML ($p = .773$).

A significant effect of Group on balance performance was also found, $F(8, 228) = 4.02$, $p < .001$, $\eta p^2 = .12$. Bonferroni corrected follow-up tests revealed that OA-F had significantly greater Area of sway ($p < .001$), Average sway velocity ($p = .001$), SD-ML ($p < .001$), and SD-AP ($p = .04$) compared to YA, and greater Area of sway ($p < .001$), SD-ML ($p = .006$) and SD-AP ($p = .007$) compared to OA-NF. There were no significant differences between YA and OA-NF in any of the sway variables (all *p*'s > .05).

3.2 ST and DT comparison for complexity-based COP sway variables

Multivariate repeated measures ANOVA revealed no significant interaction between Task condition and Group, $F(8, 228) = 0.64$, $p = .741$, $\eta p^2 = .02$. A significant effect of Task condition on balance performance was found, $F(4, 113) = 3.19$, $p = .016$, $\eta p^2 = .10$. However, Bonferroni corrected follow-up tests revealed that ST and DT performance was not significantly different for any of the complexity-based COP sway variables (all *p*'s > .05).

A significant effect of Group on balance performance was also found, $F(8, 228) = 4.75$, $p < .001$, $\eta p^2 = .14$. Bonferroni corrected follow-up tests revealed that OA-F showed significantly higher DFA-ML ($p < .001$) and significantly lower SampEn-ML ($p = .011$)

compared to YA. OA-NF showed significantly higher SampEn-AP compared to YA (p = .001). There were no other significant differences between the three groups.

3.3 Tone-counting accuracy

Mean tone-counting accuracy (calculated as the absolute percent concordance between participants' reports and number of tones actually presented, see Maxwell, Masters, & Eves, 2000) was 97.61 (SD = 4.03), 91.45 (SD = 12.67) and 90.50 (SD = 13.64), for YA, OA-NF and OA-F, respectively. Univariate Analysis of Variance revealed that tone-counting accuracy was significantly different between the groups, $F(2,118) = 5.91$, $p = .004$, $\eta p^2 = .09$, with YA being more accurate than OA-NF (p = .023) and OA-F (p = .009). There was no significant difference between the latter two groups (p = 1.0).

Table 2 Mean (SD) scores of traditional (Area, average velocity, SD-ML, SD-AP) and complexity-based (SampEn-ML, SampEn-AP, DFA-ML, DFA-AP) COP measures during single-and dual-task balance performance by young adults, older adult non-fallers and older adult fallers.

	Young adults		Older non-fallers		Older fallers	
	ST	DT	ST	DT	ST	DT
Area of sway	103.38 (63.82)$^{\#}$	104.39 (65.68)	109.88 (63.37)$^{\#}$	99.54 (52.46)$^{\#}$	180.26 (97.86)*†	143.47 (96.71)†
Average velocity	6.14 (1.33)$^{\#}$	5.95 (1.32)$^{\#}$	7.05 (1.95)	6.56 (1.74)	7.66 (1.90)*	6.96 (1.73)*
SD-ML	2.14 (0.83)$^{\#}$	2.21 (1.03)$^{\#}$	2.28 (0.88)$^{\#}$	2.30 (0.93)	3.02 (1.02)*†	2.83 (1.31)*
SD-AP	4.17 (1.53)$^{\#}$	4.07 (1.61)	4.03 (1.45)$^{\#}$	3.75 (1.50)	5.13 (1.55)*†	4.19 (1.25)
SampEn-ML	0.18 (0.09)$^{\#}$	0.18 (0.10)	0.17 (0.06)	0.16 (0.07)	0.13 (0.04)*	0.14 (0.07)
SampEn-AP	0.08 (0.03)†	0.08 (0.03)†	0.10 (0.03)$^{*\#}$	0.10 (0.03)*	0.08 (0.03)†	0.09 (0.03)
DFA-ML	1.36 (0.12)$^{\#}$	1.37 (0.11)$^{\#}$	1.39 (0.08)$^{\#}$	1.41 (0.09)	1.46 (0.09)*†	1.44 (0.10)*
DFA-AP	1.52 (0.07)	1.53 (0.07)	1.49 (0.08)	1.50 (0.09)	1.52 (0.09)	1.53 (0.10)

Note: * $p < 0.05$ from young adults; $^{\dagger}p < 0.05$ from older non-fallers; $^{\#}$ $p < 0.05$ from older fallers

Abbreviations: ST, single-task; DT, dual-task

3.4 Movement Specific Reinvestment Scale (MSRS) scores

Univariate Analysis of Variance revealed a significant difference for MSRS scores between YA, OA-NF and OA-F, $F(2,116) = 12.91$, $p < .001$, $\eta p^2 = .18$. Follow-up tests revealed that YA (*Mean* = 40.76) scored significantly higher on the scale compared to OA-NF (*Mean* = 30.53) and OA-F (*Mean* = 28.68). There was no significant difference between OA-NF and OA-F ($p = 1.0$).

3.5 Correlation and regression analysis

Correlations between MSRS score and the COP variables for single-task and dual-task performance are presented in Table 3 and Table 4, respectively. MSRS score was significantly correlated with SD-ML (r = 0.32, $p = .027$), SampEn-ML (r = -0.33, $p = .023$) and DFA-ML (r = 0.30, $p = .040$) for YA under single-task condition. Simple linear regression analyses indicated that scores on the MSRS explained 9.9% ($b = 0.03$, $\beta = 0.32$, $t(47) = 2.28$, $p = .027$), 10.6% ($b = -0.004$, $\beta = -0.33$, $t(47) = -2.36$, $p = .023$), and 8.7% ($b = 0.004$, $\beta = 0.30$, $t(47) = 2.12$, $p = .040$) of the total variation in SD-ML, SampEn-ML, and DFA-ML, respectively, for YA under single-task conditions. Under dual-task condition, however, none of the COP variables were correlated with MSRS. For OA-NF and OA-F, MSRS score was not significantly correlated with any of the COP variables under either single-task or dual-task conditions (all *p*'s > .05).

Table 3 Correlation matrix for Movement Specific Reinvestment scores and all COP variables in the single-task condition

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Young adults								
1. MSRS	-							
2. Area	0.16	-						
3. Velocity	-0.02	0.50*	-					
4. SD-ML	0.32*	0.80*	0.39*	-				
5. SD-AP	-0.12	0.75*	0.34*	0.30*	-			
6. SampEn-ML	-0.33*	-0.52*	0.08	-0.76*	-0.17	-		
7. SampEn-AP	0.15	-0.41*	0.22	-0.06	-0.72*	0.15	-	
8. DFA-ML	0.30*	0.53*	-0.11	0.70*	0.16	-0.80*	-0.12	-
9. DFA-AP	-0.06	0.45*	-0.23	0.17	0.63*	-0.29*	-0.84*	0.39*
Older adult non-fallers								
1. MSRS	-							
2. Area	0.01	-						
3. Velocity	0.08	0.75*	-					
4. SD-ML	0.02	0.85*	0.74*	-				
5. SD-AP	0.11	0.73*	0.48*	0.35*	-			
6. SampEn-ML	-0.20	-0.53*	-0.21	-0.72*	-0.10	-		
7. SampEn-AP	0.02	-0.18	0.29	0.24	-0.64*	-0.12	-	
8. DFA-ML	-0.15	0.37*	-0.01	0.42*	0.11	-0.71*	-0.05	-
9. DFA-AP	-0.12	0.06	-0.37*	-0.27	0.48*	0.09	-0.85*	0.16
Older adult fallers								
1. MSRS	-							
2. Area	0.03	-						
3. Velocity	0.03	0.76*	-					
4. SD-ML	0.01	0.82*	0.80*	-				
5. SD-AP	-0.05	0.78*	0.46*	0.39*	-			
6. SampEn-ML	0.02	0.52*	-0.23	-0.71*	-0.14	-		
7. SampEn-AP	0.10	-0.20	0.30	0.25	-0.64*	-0.13	-	
8. DFA-ML	-0.15	0.41*	0.01	0.36*	0.22	-0.67*	-0.15	-
9. DFA-AP	-0.15	0.31	-0.26	-0.09	0.55*	-0.11	-0.86*	0.41*

Note*: * $p < 0.05$*

Table 4 Correlation matrix for Movement Specific Reinvestment scores and all COP variables in the dual-task condition

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Young adults								
1. MSRS	-							
2. Area	0.14	-						
3. Velocity	-0.07	0.42*	-					
4. SD-ML	0.07	0.83*	0.34*	-				
5. SD-AP	0.17	0.69*	0.38*	0.28	-			
6. SampEn-ML	-0.05	-0.63*	0.01	-0.82*	-0.06	-		
7. SampEn-AP	-0.08	-0.45*	0.12	-0.10	-0.76*	0.11	-	
8. DFA-ML	0.16	0.54*	-0.20	0.55*	0.17	-0.79*	-0.26	-
9. DFA-AP	0.09	0.48*	-0.15	0.22	0.55*	-0.33*	-0.76*	0.51*
Older adult non-fallers								
1. MSRS	-							
2. Area	-0.06	-						
3. Velocity	0.01	0.53*	-					
4. SD-ML	-0.08	0.76*	0.26	-				
5. SD-AP	0.05	0.67*	0.48*	0.09	-			
6. SampEn-ML	0.09	-0.46*	0.22	-0.75*	0.04	-		
7. SampEn-AP	-0.11	-0.22	0.26	0.20	-0.65*	0.04	-	
8. DFA-ML	-0.08	0.39*	-0.24	0.44*	0.15	-0.69*	-0.20	-
9. DFA-AP	0.02	0.22	-0.34*	-0.14	0.56*	-0.09	-0.86*	0.40*
Older adult fallers								
1. MSRS	-							
2. Area	-0.23	-						
3. Velocity	-0.05	0.48*	-					
4. SD-ML	-0.13	0.88*	0.50*	-				
5. SD-AP	-0.24	0.73*	0.33	0.36*	-			
6. SampEn-ML	0.08	-0.60*	-0.12	-0.75*	-0.18	-		
7. SampEn-AP	0.12	-0.28	0.54*	0.01	-0.56*	0.09	-	
8. DFA-ML	-0.07	0.58*	0.04	0.59*	0.31	-0.68*	-0.29	-
9. DFA-AP	-0.11	0.37*	-0.50*	0.10	0.54*	-0.15	-0.93*	0.36*

Note: * $p < 0.05$

4. Discussion

We first compared the balance performance of young adults (YA), older adult non-fallers (OA-NF) and older adult fallers (OA-F) under single-task and dual-task conditions. Similar to some previous findings (e.g., Maki, Holliday, & Fernie, 1990; Shumway-Cook et al., 1997), we found no significant differences in balance performance of YA and OA-NF. OA-F, however, exhibited significantly greater area of sway, sway velocity and sway amplitude in the anterior-posterior direction than YA, and greater area of sway and sway amplitude in the medial-lateral and anterior-posterior directions than OA-NF. Complexity-based measures revealed a more constrained mode of balance in the medial-lateral direction (i.e., higher regularity) for OA-F compared to YA. Interestingly, YA showed a more constrained mode of balance in the anterior-posterior direction compared to OA-NF. We do not have a good explanation for these results. Under secondary task loading, participants displayed smaller sway velocity and sway amplitude in the anterior-posterior direction compared to the single task condition. Better performance under dual-task conditions suggests that by occupying cognitive resources available for conscious control of movement balancing task was performed in a more proceduralised manner.

We found that conscious motor processing, measured using the Movement Specific Reinvestment Scale (MSRS; Masters et al., 2005), was related to postural control in YA under single-task condition, with higher scores on the Scale (i.e., higher propensity for conscious control of movement) associated with greater sway amplitude and a more constrained mode of balance in the medial-lateral direction. Scores on MSRS predicted approximately 9-10% of the total variability in medial-lateral sway measures. The anatomy of the lower limbs has been argued to favour less medial-lateral than anterior-posterior sway during quiet standing (Mochizuki, Duarte, Amadio, Zatsiorsky, & Latash, 2006). Less sway may make it easier, or provide more opportunity, to consciously control sway in the medial-lateral direction, which would explain why medial-lateral sway but not anterior-posterior sway was associated with movement specific reinvestment. As we expected, scores on the MSRS were not associated with our balance measures under dual-task conditions, presumably because secondary-task loading '*left minimal space'* for conscious motor processing.

These findings suggest that movement specific reinvestment plays a role in maintaining stable posture in young adults and that non-traditional complexity-based COP measures in conjunction with traditional COP measures provide a window into the role of consciousness in balance. However, present findings do not inform about the association between the propensity for movement specific reinvestment and situations that cause threat to posture (i.e., situations in which good balance is vital). Given that the ultimate goal of the postural control system is to maintain upright stance, future research should aim to examine how propensity for movement specific reinvestment affects recovery from unexpected balance perturbations.

Interestingly, we found no association between scores on the MSRS and any of the COP measures for either OA-NF or OA-F. There are several possible explanations. First, although we have argued that high complexity refers to the presence of non-random fluctuations (i.e., long-range correlations) in balance control, it is possible that random fluctuations (noise) were captured. Indeed, Borg and Laxåback (2010) argued that ageing systems lose their structure and provide less precise input for postural control. Due to random fluctuations in the balance control of older adults, complexity-based measures (and traditional COP measures), may therefore be disassociated from self-reported subjective measures of conscious involvement in motor performance.

A second possible explanation is that for older adults scores on the MSRS do not represent the true amount of conscious involvement that they have in their movements. It has been previously shown that older adults often misperceive their action capabilities (e.g., Oxley, Ihsen, Fildes, Charlton, & Day, 2005; Zivotofsky, Eldror, Mandel, & Rosenbloom, 2012), possibly as a consequence of diminished cognitive functioning or reduced levels of physical activity. It is, therefore, possible that they also misjudge how they process information related to their actions/movements. We deem this explanation unlikely, given that we have previously shown that older adults who scored higher on the MSRS were more aware of their limb movements during walking than those who scored lower (Uiga, Capio, Wong, Wilson, & Masters, 2015). Such a finding supports the efficacy of the MSRS to reliably distinguish between older adults with a high or a low propensity for conscious control of their movements during locomotion.

These findings suggest that there are fundamental differences in conscious processes underlying balance and walking. One of the assumptions of the Theory of Reinvestment is that in order for reinvestment to occur, the performer must have access to declarative knowledge about the task (Masters & Maxwell, 2008; Masters et al., 1993). Given the phylogenetic nature of postural control, it is possible that in contrast to undergraduate sport science students who learn about the mechanics of postural control, older adults did not have access to declarative knowledge of balancing and were therefore unable to reinvest.

That it is possible at all to have declarative knowledge about balancing has been shown before. For example, Orrell, Eves, and Masters (2006) asked participants to learn a stabilometer balancing task either by using discovery learning (i.e., participants were encouraged to discover the rules of the task) or by implicit learning (i.e., participants learnt the skill using either analogy or errorless learning). They found that discovery learners accumulated significantly more rules ($M = 2.83$) about the task than implicit learners. Furthermore, Zaback, Carpenter, and Adkin (2016) showed that participants reported significantly more information about movement processes of balancing (e.g., "I focused on making sure not too much of my weight was on the balls of my feet because then I would be leaning forwards and I didn't want to fall", p. 21) during high postural threat conditions compared to low postural threat conditions.

This study is not without limitations. First, the quiet standing balance task is a relatively easy task to perform and might not have been sufficient to cause conscious movement processing in older adults who have been performing the task for several decades. The use of more challenging balance conditions, such as narrow or tandem stance, might be more likely to induce conscious processing of movements. Second, we used MSRS as a trait measure to inform our understanding of the predictive validity of the Scale; however, state measures of conscious movement processing (i.e., using MSRS scale as a context specific measure or assessing neural activity), would have been likely to complement the current results and perhaps inform about the conscious processes underlying balance performance by older adults. Finally, the older adults who participated in the study were healthy, active Hong Kong elderly, who might not represent an average older adult in other communities.

To conclude, we have shown that the propensity for conscious control of movements is related to the complex dynamics of postural control, and to movement amplitude in the medial-lateral direction, in young adults under single-task conditions. Under dual-task condition, however, the association disappears, supporting the notion that secondary task loading reduces resources available for conscious control. We found no relationship between propensity for conscious control of movements and the balance performance in older adults. To untangle the underlying causes for these findings, further research that examines the accumulation of balance-specific declarative knowledge, is recommended.

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Conflict of interest

The authors confirm that there are no conflicts of interest regarding the current manuscript.

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